THE ENERGY CONDITIONS NECESSARY TO PRODUCE THE RÖNTGEN RAYS.

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This paper is a preliminary study of the conditions which exist in highly rarefied media under discharges of electricity, conducted by means of the large storage battery of the Jefferson Physical Laboratory.

The value of a large storage battery for the study of the discharge of electricity through gases has long been recognized, and such batteries of 1,800 to 2,000 cells have been constructed by Zehnder, by Quincke, and others. Quincke devotes a large portion of a recent article* to a description of the details of construction of such a battery of 1,200 cells. The battery of the Jefferson Physical Laboratory consists of 10,000 cells, and it is of such practical construction that I believe a detailed account of it will be of advantage to those contemplating the installation of a similar one. When I was considering the cost of such a battery, Professor B. O. Peirce, my colleague, expressed the opinion that dry wood would serve perfectly well for insulating material; and the mechanician of the Laboratory, Mr. G. W. Thompson, coinciding in this opinion and deprecating the use of vulcanite or any of the forms of insulators in the market, on account of the loss of insulation due to surface action, I decided to adopt wood for the supports of the cells of the battery.

There are 10,000 cells, each one consisting of a test tube $5\frac{1}{2}$ inches long and 25 mm. diameter, shown in elevation and plan in Figure 1 and Figure 2. The plates of the cell are strips of lead 1 mm. thick, 12 mm. broad, which have been run through a peculiar mill to give them a corrugated surface. The strips do not reach to the bottom of the tubes, in order to avoid short circuiting due to a possible falling off of the peroxide of lead. They are separated by rubber bands, *B*, and

* Annalen der Physik und Chemie, No. II. p. 417, 1896.

the terminals of the cells are made of thick lead wire, which are led through wooden supports far from any possibility of corrosion where they connect to the copper wires of the main circuits. The unit of the battery consists of three test tubes, mounted in holes bored in blocks of wood $5 \times 5 \times 15$ cm. (U, Figs. 1 and 2). These blocks of wood are boiled in paraffine, and the tubes are held upright by means of paraffine, which is poured into the holes in which the tubes are inserted, these holes being made slightly larger than the tubes. On solidification the tubes are held upright. There are twenty of such blocks on each shelf of one upright case, thus making sixty cells to a shelf; and there are seven shelves to a case, making four hundred and twenty cells to a case. On the back of such cases are arranged knife-edge switches, which enable me to arrange the cells in multiple or in series, — to employ one shelf or the entire number. At the extremity of each row of six cases is a switch board with similar switches, which enable me to use one case or any combination of the entire number of six cases. These switch boards consist of dry whitewood, the insulation of which has been found to answer perfectly. Since the practical success of such a large battery depends upon the ease with which the cells can be charged in multiple and discharged in series, I have represented the scheme of connections of two shelves, sixty cells on each case. The remaining cells on successive shelves of each case are connected in a similar manner. A and A' (Fig. 3) represent the terminals of each line of twenty cells. Their lead terminals are led to the back of the case, where there are switches which have pivots at the points E and D. These switches, revolving about the pivots E and D, connect the terminals of the cells to a wire running through the pivots E, and through the points L; in which case the cells are in multiple. If, however, the points N' and N'' are thrown out by revolving the switches about E, and the points L of the switches are connected to N' and N'', the cells are thrown into series. This operation can be quickly accomplished, the points N' and the points N'' moving together, and also the points L moving together about the pivots D. In arrangement for series, therefore, the current goes from D to N', then to A, then through the row of twenty cells to A', thence to D, to N', and to A, again to A', and then to the next row of switches corresponding to the next shelf, and so on.

A similar plan of switch boards has been erected for each half of the entire battery, consisting of five thousand cells, in order that one half of the battery may be used, or the entire number of cells. At the experimental table to which the terminals of the battery are led there are

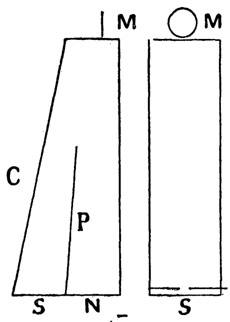

Fig 6

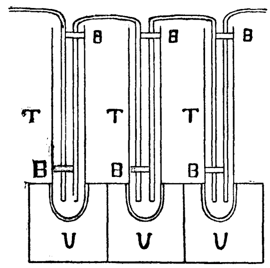

Fig 1

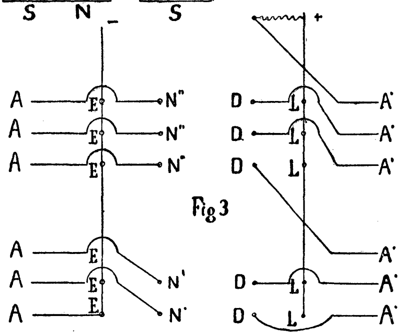

Fig 3

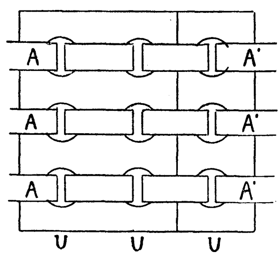

Fig 2

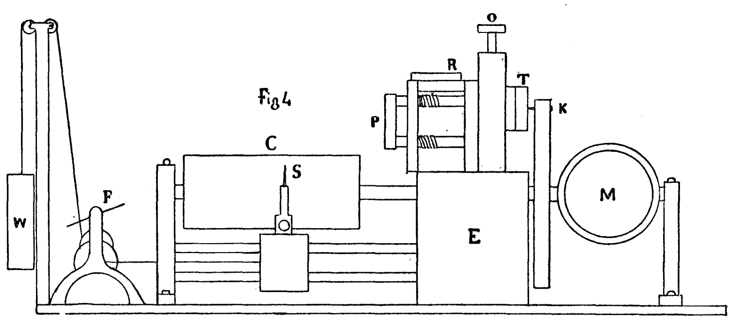

Fig 4

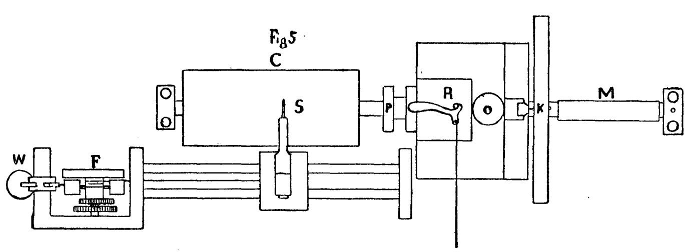

Fig 5

two distilled water resistances which enable one to control the strength of current of the battery. The cells are charged in multiple with only twenty in each branch of the divided circuit; and they are always left on the multiple circuit when not in use. The resistance of each cell is about one fourth of an ohm, and the electromotive force about 2.1 volts. A study of the voltage of each case by means of a voltmeter showed that the voltage could be closely estimated by knowing the number of cells.

The Planté rheostatic machine, by means of which one can rise from the voltage of the battery (20,000) to 500,000 volts,* is a practical modification of that described by its author. Instead of mica plates, the mechanician of the Laboratory, Mr. Thompson, selected glass plates 8×10 inches, one tenth of an inch thick: these were coated with tinfoil to within one inch of the edges of the plate. At first it seemed doubtful whether glass of this thickness would stand the high voltages to which it would be subjected. Preliminary experiments, however, showed that this thickness of glass would stand a steady stress of twenty thousand volts, — although it would break down under much less voltage arising from alternating stresses. I have employed thirty of such glass condensers or Franklin plates, which are charged in multiple by the battery of from five thousand to ten thousand cells; that is, all the coatings of one side of the plates are connected with the — pole of the battery, and the coatings of the other side with the + pole of the battery. The change from multiple to series is accomplished by a series of brushes which are arranged on two vulcanite rods. These brushes are connected with the coatings of the glass plates. A revolving drum provided with pins and connecting wires is driven by an electric motor, and serves rapidly to change the connection of the condensers from multiple to series.

Starting from the point reached by De La Rue and Müller, about 15,000 volts, the Planté rheostatic machine shows that the length of spark is closely proportional to the electromotive force. On plotting lengths of sparks as ordinates, and NV as abscissas, N being number of Franklin Plates, a straight line is obtained.

The method I have employed for studying the energy conditions in Crookes tubes, and in the production of electrical discharges in general, may be termed the damping of an additional spark method, or the comparison of resistances by the estimation of the damping of electrical oscillations.† The electrical circuit is provided with two spark gaps. One

* Comptes Rendus, Tom. LXXXV. p. 794, Oct. 29, 1877.

† Damping of Electric Oscillations, These Proceedings, Vol. XXVI.

of these is placed in a gas or under the conditions which are to be examined, while the other is protographed according to Feddersen's method by a revolving mirror. A previous study of the behavior of various electrodes had led me to select cadmium for the terminals of the spark gap which are examined by the revolving mirror. The light from cadmium is very actinic; and with carefully pointed terminals shielded from the currents of air produced by the revolving mirror, very sharp photographs of electrical oscillations can be obtained. The resistance of a spark in air or in rarefied media can be estimated by this method to one half an ohm.

The revolving mirror which I employed was the one I have used in previous researches.* It is a glass concave mirror of ten feet focal length, silvered on its concave surface, and corrected for the use to which it was put. The improvements in electric motors and storage batteries enables one to obtain great steadiness of rotation. The accompanying figure represents the revolving mirror, together with the electric motor and the chronograph, and the diagram explains the parts. Figure 4 is the apparatus in elevation, and Figure 5 in plan. *M* represents the mirror, *E* the motor, *C* the chronograph, *S* the stylus, *K* the cutting tool for obtaining electrical contact at the instant the mirror reaches a definite angle in its revolution. This cutting tool passes through a strip of type metal, *T*. This strip is adjusted up and down by the screw *O*, and is adjusted in a direction at right angles by the spring bolt *P*. The catch *R* releases *P*, at any desired moment, by means of a tension on a string connected to it. The stylus *S* is drawn along guides by a string which is connected through clockwork to a weight, *W*. A fan, *F*, serves to control the movement of *S*. The stylus is also released by a catch which can be tripped at any moment by the operator.

The camera consisted of a box ten feet long, made of a trussed frame covered with black cloth. This camera is shown in plan and elevation in Figure 6. *M* is the revolving mirror, *C* the camera, *S* the spark gap, *P* a partition which extends one quarter way through the interior of the camera to shield the photographic plate at *N* from the direct light from the spark gap *S*. The photographic room in which this camera is placed was about twenty-five feet square, and was provided with shutters of orange fabric. In one corner of the room is the developing closet. The same room contains a mercury pump for exhaus-

* Phil Mag., 1894; Am. Journal of Science, 1894; Velocity of Electric Waves, Am. Journal of Science, 1895.

tion, and the wires from the storage battery are led to a switch board in this room. A connecting room contains a Rowland grating.

With the facilities at my command, I set to work to investigate the conditions which seem to be necessary to produce the Röntgen rays. I have said that my previous experience in studying oscillatory discharges had led me to select cadmium for the material of the terminals of a spark gap. The light is highly actinic and with not too strong discharges, and with sharply pointed terminals well defined images of even minute evidences of oscillations can be obtained. I have also experimented with various developers, and finally adopted Rodinol. This developer works with great intensity, and quickly brings out the latent images. The study of rapid electrical oscillations enables one to estimate with considerable accuracy the merits of different developers for instantaneous photography. With a definite electrical circuit consisting of a known capacity (Leyden jar) and a known self-induction, together with constant rate of speed of the revolving mirror, one can obtain the time of exposure; and the number of oscillations brought out by the various developers is a guide to their relative values.

Having at my command a battery giving a voltage of twenty thousand, with an internal resistance of only one quarter of an ohm per cell, and therefore capable of giving a very powerful current, I first studied the behavior of Crookes tubes, which were directly connected to the terminals of this battery. I speedily discovered that no Röntgen rays could be obtained with a voltage of twenty thousand. On strongly heating the Crookes tubes they were filled with a pale white light, which showed very faint bands in the green when examined by a spectroscope. After a short interval, the entire strength of the battery appeared to be manifested in the tubes, the electrodes became red-hot, the medium apparently broke down, and offered little resistance to the battery current. This white discharge showed, even at its culminating point, no Röntgen rays, and appeared to be of the nature of a voltaic arc discharge. I then employed the Planté rheostatic machine. I found that at least one hundred thousand volts were necessary to produce the Röntgen rays, and that they were produced more intensely as I increased the voltage, — certainly to the point of five hundred thousand volts. In order to ascertain how great a loss occurred in this machine on discharging in series, I investigated the length of spark obtained by varying the number of Leyden jars in this machine. Experiments to be described later in this paper had shown me that increase of electromotive force diminished the resistance offered to a spark in air. The higher the electromotive

force, therefore, employed to charge the jars, the less resistance would occur at the brushes where the change from multiple to series occurred, and therefore the less the loss of energy due to Joule's heat. I therefore investigated the length of spark obtained from the Planté machine by continuing the curves plotted by De La Rue and Müller,* and found that, starting with 10,500 volts, and increasing the Leyden jars progressively, the length of sparks plotted as ordinates and the rise in voltage (NV) gave a straight line which was an extension of those obtained by them. Furthermore, as will be shown later, differences between points and planes, and points and paraboliform surfaces disappeared with high voltages. In order to ascertain if the discharges through Crookes tubes when the Röntgen rays were apparently produced most strongly were oscillatory, I first placed a Geissler tube in the circuit with the Crookes tube, and carefully observed the appearances at the two electrodes of the Geissler tube. The electrodes were quite alike in appearance, and indicated an oscillatory discharge. I then replaced the Geissler tube by a small spark gap, and photographed it in the rapidly revolving mirror.

The photograph showed ten clearly defined oscillations, with a period of about one ten-millionth of a second, with the Crookes tube and the circuit I employed. Furthermore, applying the method of estimating resistances by the method of damping, I found that the resistance of the rarefied medium was less than five ohms. The energy therefore at the moment of the emission of the Röntgen rays was not far from 3,000,000 horse power acting for one millionth of a second. The Crookes tube which I employed was of the focus tube pattern (King's College, London). I also employed a Crookes tube with an aluminium mirror of about two centimeters' focus. The resistance of this tube to the discharge was approximately the same as that in which the mirror had a focal length of about five centimeters. There seemed to be no advantage in shortening the distance between the anode and the kathode in a Crookes tube. Struck by the fact that the distance between the electrodes did not appear to make any appreciable difference in the resistance offered by the Crookes tube to oscillating currents, I replaced the tube by a spark gap in air of six inches in length, and photographed the spark in another gap in air in the same circuit. This latter gap was 6 mm. in length. The photographs showed on the average the same number of oscillations, both when the additional spark gap was six inches

* Proc. Roy. Soc., Vol. XXXVI. p. 151, 1883–84.

in length and when it was one inch in length. I found, moreover, on increasing the electromotive force, that the resistance of the sparks in air decreased. By quickly drawing apart the terminals of the large storage battery of ten thousand cells, a flaming arc discharge can be produced in air of nearly three feet in length. Rhigi has shown also that sparks from an electrical machine or Leyden jars can be greatly increased in air by quickly drawing apart the spark terminals. We thus see that very little resistance is encountered by more than quadrupling the length of discharge.

I next placed the additional spark gap in a receiver connected with an ordinary air pump, and studied the resistance offered by rarefied air at the point when long ribbon-like white disruptive discharges can be obtained. This point is about 100 cm. pressure in the receiver. The resistance of such discharges of about six inches in length in a receiver containing air at this pressure is two or three ohms more than sparks one quarter of an inch in air. The latter offer a resistance of from two to three ohms. On measuring by the damping method the resistance of sparks of different lengths in the receiver at this pressure, no difference in resistance could be perceived between a spark of six inches in length and one of three inches in length. The method would have detected a difference of half an ohm.

The additional spark gap was next placed in a chamber of air which was compressed to four atmospheres. This amount of compression made no difference in the resistance to the disruptive discharges. It would be interesting to push this research to the amount of compression reached by Professor Dewar in the case of liquid oxygen. He has obtained a dielectric constant for liquid oxygen of 1.45. When this dielectric, however, is broken down by a disruptive spark, I am inclined to believe that it would show little more resistance than air under the same circumstances.

The additional spark gap was next placed in hydrogen gas generated at atmospheric pressure by electrolysis. No appreciable difference at this pressure was noticed between the resistance offered by this gas and air at the same pressure. The length of spark which could be obtained with a given voltage was somewhat more in hydrogen than in air. It has been shown by Professor T. W. Richards and myself that the resistance of gases at low pressures diminishes with the increase of electromotive force.* I was interested to test this question by the employment of the

* Am. Journal of Science, April, 1897.

high voltages which can be obtained by the use of the Planté machine. A Geissler tube containing hydrogen at 1 mm. pressure was placed between the terminals of the Planté machine together with a spark gap. This tube would give only four half oscillations with ten thousand volts and gave twenty half oscillations with approximately 300,000 volts, the electrical circuits being the same in the two cases.

I next placed the additional spark gap in the flame of a Bunsen burner. It is well known that the spark length can be greatly increased in an atmosphere of heated air. On photographing a spark produced in the same circuit, the resistance appeared to be slightly increased by the heated air; doubling the length of the spark, however, made no change in the resistance that was encountered in the heated medium. The phenomenon was very analogous to that observed in the receiver exhausted to 100 cm. It is well known that lightning follows currents of heated air, striking into barn doors from which arise hot air currents from hay, and passing into chimneys from which issue heated air. The striking fact is presented that the medium breaks down more easily when it is heated; but it offers during the oscillations of the lightning somewhat more resistance than cold air.

I was interested to discover whether heating the air in which the spark in the primary of the Thomson Tesla transformer is produced would have any marked effect on the high tension spark of the secondary of such a transformer. It was immediately evident that such heating of the air was detrimental. The high tension sparks immediately ceased to jump at the extreme sparking distance of the terminals. Following this train of thought, I next placed a spark gap of the primary of the above mentioned transformer between the poles of a powerful magnet, giving a field of certainly ten thousand lines to the centimeter. It is well known that when such a field is excited the primary spark appears to be blown out with a loud report, and a great increase of length of spark is obtained in the secondary of the transformer. Applying the method of estimation of resistance by damping to an additional spark gap which was placed in this magnetic field, I found no difference in resistance offered to the spark, whether the magnetic field was excited or not, or whether the spark jumped across the direction of the magnetic lines or in the same direction. Is it possible that, the ether being already under a magnetic stress, the addition of a powerful electrostatic stress serves suddenly to break down the ether? It is well known that a blast of air imitates the action of a magnetic field, and produces also a great increase of spark in the secondary circuit of a Thomson Tesla transformer. It prob-

ably does so by blowing out the voltaic arc which tends to form. It may be that the electrodynamic repulsion compels the oscillations of the spark not to follow, so to speak, the voltaic arc and its current of heated air. It seems as if the oscillations of the spark were true voltaic arcs, and that the electrodynamic repulsion blows these out. There are, however, just as many oscillations in the magnetic field as outside of it. The field exerts no influence on the number of oscillations, or on their apparent duration. The loud report which is produced when a spark is formed in a magnetic field, notably when the primary circuit of an ordinary Ruhmkorf coil is broken in a strong magnetic field, may indicate a sudden stress in the medium; in the case of the Crookes tube, the highly rarefied medium within it would effectually prevent our hearing a similar report.

In order to see if the radiations from a Crookes tube emitting Röntgen rays could produce any effect upon the primary spark of the Thomson Tesler transformer, I produced it near a Crookes tube, and examined it by the method of damping. No change in resistance could be perceived, and no effect was observed upon the length of the spark produced by the secondary of such a transformer. In the next place, I resolved to determine whether differences in the materials of the spark gap made any appreciable difference in the resistances observed in disruptive discharges. I accordingly employed terminals of platinum, iron, aluminium, brass, cadmium, zinc, and carbon. No difference arising from difference of metals could be noticed. These experiments confirm the results obtained by Rhigi * and by De La Rue and Hugo Müller.†

Moreover, no difference of resistance between spheres, between pointed terminals, or between a point and a plane, could be perceived. With powerful discharges such differences disappear. The employment of a powerful storage battery together with a Planté rheostatic machine shows conclusively that the discharge in a Crookes tube, when on the point of emitting the Röntgen rays most intensely, is an oscillatory one, and that such discharge encounters a resistance less than five ohms. An estimate of the great amount of energy thus developed in an exceedingly small interval of time can be obtained if we suppose that Ohm's law holds for individual oscillations. This reservation is an important one, for the investigations I have described in this paper show that a discharge of six inches in length encounters no more resistance during its oscillations

* Nuovo Cimento, [2.], Vol. XVI. p. 97, 1876.
† Phil. Trans., Vol. CLXIX. Pt. 1, p. 93, 1878.

than one of two inches in length. In popular language, it can be maintained that a discharge of lightning a mile long encounters no more resistance than one of a foot in length. Ohm's law does not hold for electrical discharges in air and rarefied gases. It is well known that a voltaic arc can be started in a vacuum. My experiments lead me to believe that in every case the arc is started by a spark which breaks down the medium, and the arc follows. I am led to believe that electrical oscillations are of the nature of voltaic arcs, and that the discharges in Crookes tubes are voltaic arcs. I am thus forced to the conclusion that under high electrical stress the ether breaks down and becomes a good conductor.

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